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ASD TR 7-890(II)

A. S. D. Interim Report 7-890(II)
April 1963

HYDRODYNAMIC COMPRESSIVE FORGING

Richard M. Cogan

THE GENERAL ELECTRIC COMPANY
SMALL AIRCRAFT ENGINE DEPARTMENT

Contract No. AF 33(657)-8793

A. S. D. Project 7-890

Interim Technical Engineering Report
9 October 1962 – 9 April 1963

Hydrodynamic Compressive Forging of Commercial pure aluminum with an upset ratio of 19:1 has been achieved in one operation at room temperature. The outside edge of the formed part remained square with the face throughout the forming operation. The maximum upset ratios were obtained with back pressure in the cavity in excess of the work-hardened tensile strength.

MANUFACTURING TECHNOLOGY LABORATORY

Aeronautical Systems Division
United States Air Force
Wright-Patterson Air Force Base, Ohio

Abstract Summary
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The hydrodynamic compressive die with inserts has been designed and built to withstand operating pressures of 600,000 psi at room temperature. The maximum applied load so far has been 540,000 psi, or 90% of the design limit.

Various matrix materials have been evaluated with Cerrobend having the best overall properties for use in this type die system.

The aluminum billets worked by Hydrodynamic Compressive Forging increased in Brinell hardness (500kg load - 10mm ball) from 25 to the 60/65 range.

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FOREWORD

This Interim Technical Documentary Progress Report covers the work performed under Contract AF 33 (657) 8793 from 9 July 1962 to 9 October 1962. It is released by the authors for information only and does not necessarily represent the recommendations, conclusions, or approval of the Air Force.

This program is being performed by the Small Aircraft Engine Department, Flight Propulsion Division, General Electric Company for the Aeronautical Systems Division Manufacturing Technology Laboratory Project Number 7-890 "Hydrodynamic Compressive Forging." It is being administered under the direction of Mr. G. W. Trickett (ASRCTB) Aeronautical Systems Division Wright-Patterson Air Force Base, Ohio.

Mr. Richard M. Cogan is the Project Manager, others co-operating in the investigation and preparation of the report are F. S. Dorman and A. R. Arsenault. The primary objective of the Air Force Manufacturing Methods Program is to increase producibility, and improve the quality and efficiency of fabrication of aircraft, missiles, and components thereof. This report is being disseminated in order that methods and/or equipment developed may be used throughout industry, thereby reducing cost and giving "MORE AIR FORCE PER DOLLAR."

Your comments are solicited on the potential utilization of the information contained herein as applied to your present or future production programs. Suggestions concerning additional manufacturing methods development required on this or other subjects will be appreciated.

PUBLICATION REVIEW

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Thomson Engineering Laboratory

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TABLE of CONTENTS

HYDRODYNAMIC COMPRESSIVE FORGING

BY

Richard M. Cogan

INTRODUCTION

This report covers the work done from 9 October 1962 to 9 April 1963 under contract with the Aeronautical Systems Division Wright-Patterson Air Force Base to investigate the basic parameters of the process and its application to a complex shape.

The phenomenon of increased ductility of materials in a hydrostatic environment has been demonstrated by previous investigations. The effect has been studied on simple tension with a superimposed hydrostatic pressure by P. W. Bridgman at Harvard University as early as 1909 which showed an increase in plastic deformation prior to fracture.

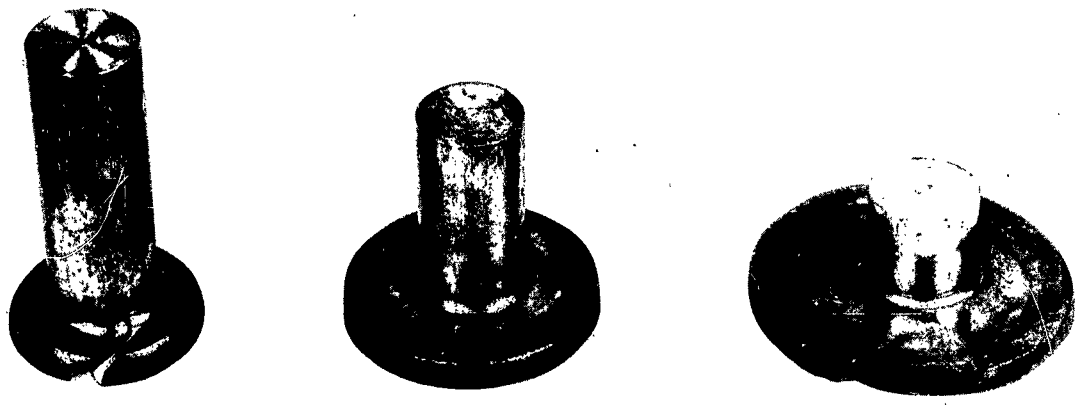
The initial feasibility investigations of the phenomenon, as it applied to closed die forging, was conducted in 1958 by the General Electric Company in Cincinnati, Ohio.

Additional work at Small Aircraft Engine Department was done in early 1962 to determine the effect on various materials. Figures 1 and 2 show the deformation achieved on two aluminum alloys.

An explanation of this increased ductility could be the high hydrostatic pressure prevents the formation of voids about discontinuities or internal flaws in the material which may act as points of fracture initiation. Another theory to explain the large amounts of deformation obtained with a superimposed hydrostatic pressure is; fracture actually occurs on a minute continuous basis but the surfaces across the fracture are not removed from each other and the hydrostatis pressure restores the integrity of the material by pressure welding.

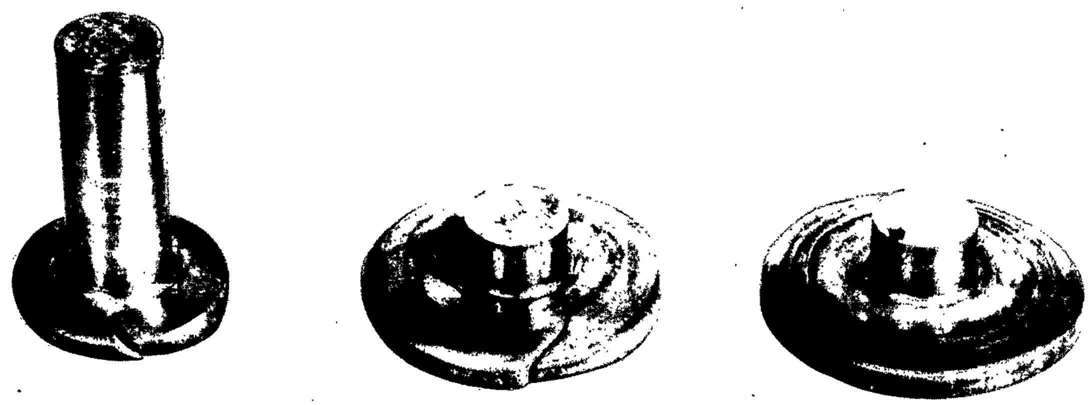
The concept of upset forging, or closed die cavity forging at room temperature into a high hydrostatic pressure then should increase the amount of plastic flow of the material prior to fracture.

The approach taken in this contract to apply the hydrostatic pressure is as follows:



A B C

Figure 1. 2011(0) Aluminum. (A) no back pressure, (B and C) with cerrobend in the cavity to provide a back pressure while being formed.



A B C

Figure 2. 6061(0) Aluminum. (A) no back pressure, (B and C) with cerrobend in the cavity to provide a back pressure while being formed.

A die was manufactured to withstand low cycle loads up to 600,000 psi by prestressing a carbide chamber with shrink fit steel rings. The carbide has an entrance chamber to the die cavity having the shape of the part to be formed. The cavity is first filled with a matrix material that becomes viscous under pressure and able to transmit pressure hydrostatically. As the billet material enters the shaped cavity it displaces the matrix material via exhaust ports provided for this purpose. The billet material replaces the matrix in the die cavity which exerts a pressure on the deforming billet due to the restricted flow of the matrix. The pressure in the die cavity is dependent on the strength of the matrix material, area of the exhaust ports, the rate it is displaced and the general die design.

TOOLING

The Clifton 600 ton press was used with a top cylinder to actuate a .375" diameter x 2.25" long carbide punch (Figure 3) independent of the press movements. This allows the 600 tons to be applied as a means of clamping the dies together. With the maximum die cavity of 1-5/8" in diameter this provides a die cavity pressure capability of 600,000 psi. As a safety measure, the punch movement is remote control with a means of reducing the applied pressure at a given rate.

The die design as reported in the first quarter report (A.S.D. Interim Report 7-890 (I)) was based on prestressing the carbide center to 500,000 psi with shrink rings. With this as a target, interference for each ring was calculated (Figure 4).

After manufacture, the die rings were strain gaged with Budd Metalfilm type CG-121 gages. These were bonded to the die rings as shown in Figure 5 with Eastman 910 cement.

The carbide center was pressed into the buffer ring which required 60 tons using Molykote as a lubricant between the interfaces. Ring "D" was then pressed into "E" with a press load of 150 tons. Ring "C" was then placed into the assembly of "D and E" to check the drop dimension (Figure 6). This was done to check the amount of interference the next ring would be subjected to against the calculated amount.

As the rings were assembled, the various strain gages were checked with a Baldwin SR-4 strain indicator and drop checks were taken at each stage of assembly.

The drop check on sub-assembly "A and B" with "C, D and E" was found to be within the expected tolerance so they were loaded to the maximum press capacity of 600 tons. This set the assembly within .060" of bottom, additional tonage was then applied with no success in final setting of the assembly.

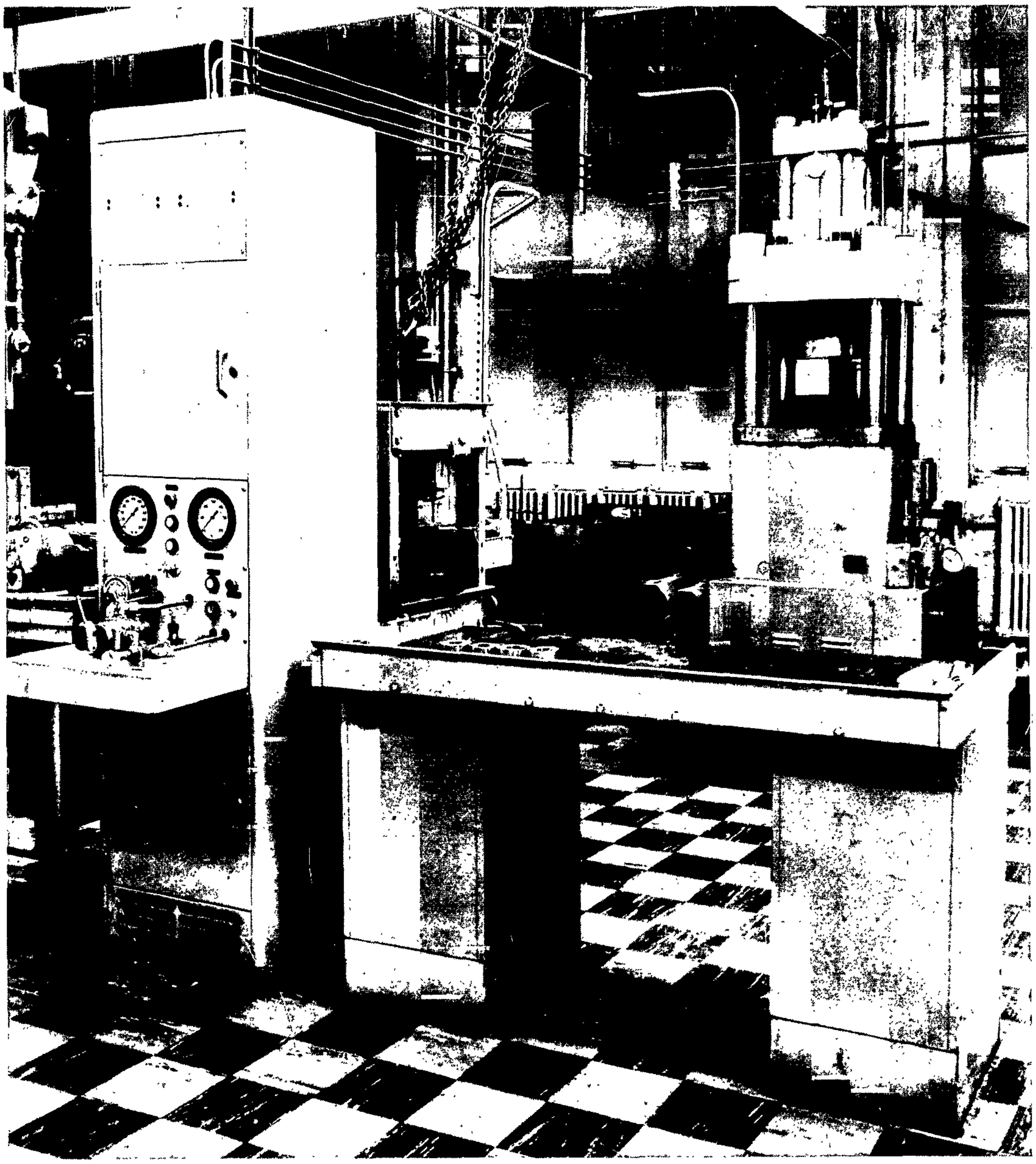


Figure 3. 600 Ton Press and Controls

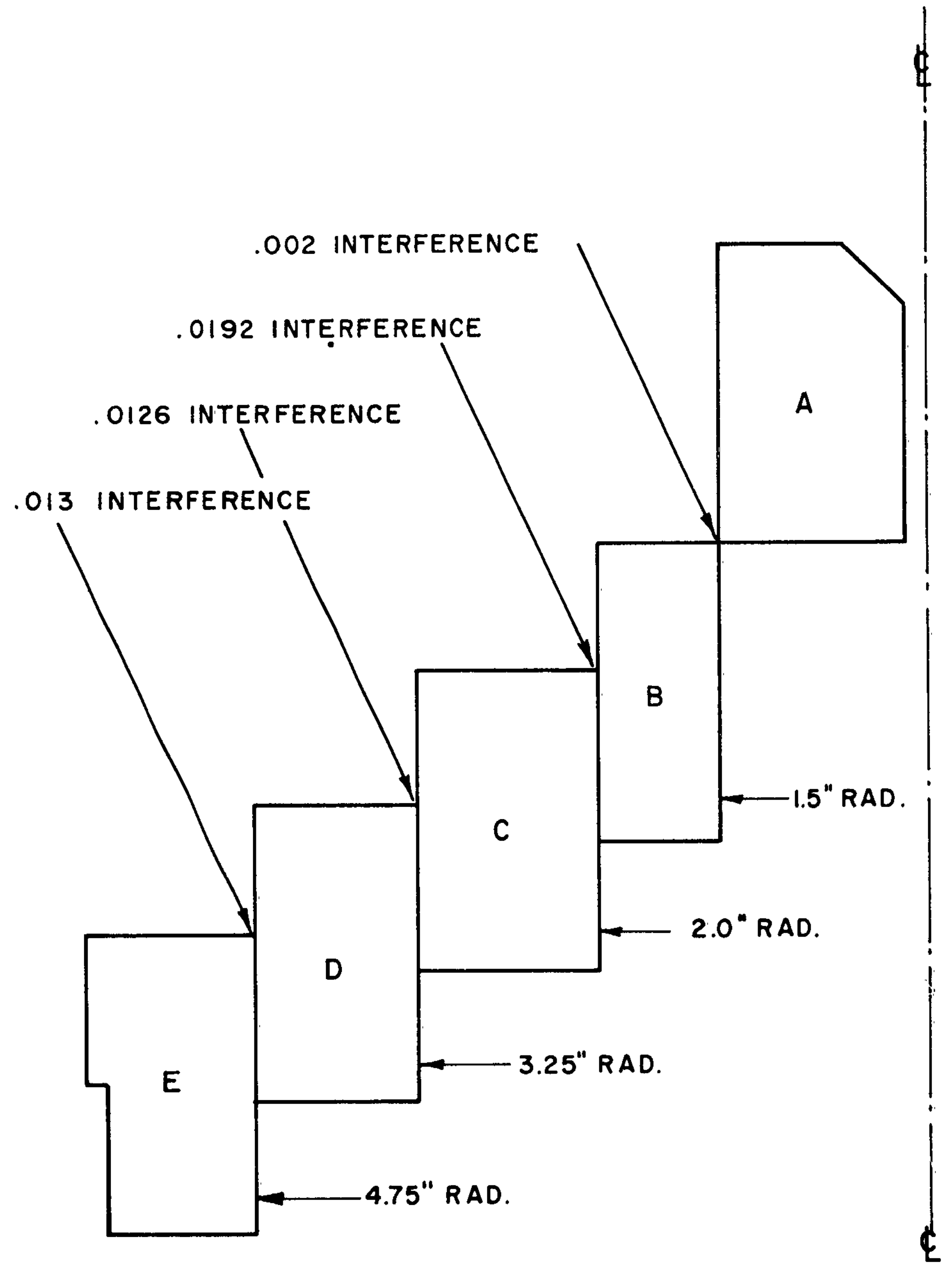


Figure 4. Interference fit between cylinders to produce compressive prestress on the carbide center ring (A).

Figure 5. Bonding of strain gages to die rings before assembly.

A close examination of the die showed the sub-assembly "A and B" was cocked. The die was then disassembled which fractured the carbide center and its buffer ring (Figure 7). Another set of rings was then prepared with a lower amount of prestress, 400,000 psi, using the same procedure for assembly as on the first die. This level of prestress allows the internal pressure to be run at 500,000 to 550,000 psi which is high enough to determine the process capabilities and the majority of its control parameters on the low strength alloys.

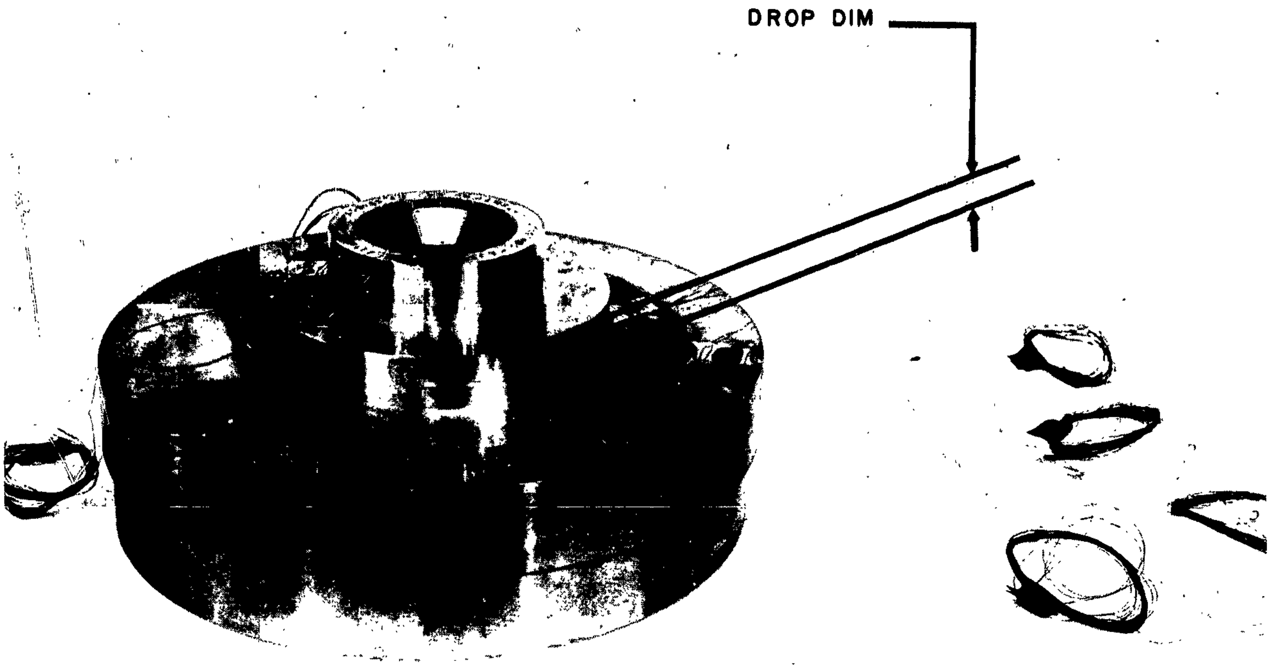


Figure 6. Drop check of height to determine interference.

Figure 7. Fractured carbide center from the first die assembly.

FLOW STUDY

To determine the flow characteristics of a material being upset into a shaped cavity, laminated color molding clay was built up into one (1) inch diameter billets. Two lamination directions were checked as shown in Figure 8.

The die used was made of aluminum rings (Figure 9) to allow for changing:

1. Cavity height
2. Feeding the billet from both ends
3. Using tubular shaped billets
4. Changing the type exhaust ports

Observations made due to the above changes were:

1. In all cases the flow pattern remained the same (Figure 10), when the billet was fed from both sides a mirror image was produced (Figure 11).
2. Billets pushed into a matrix of Dux Seal did not fracture.
3. Changing the method of matrix exhaust caused the material to flow toward the ports, the path of least resistance.

It can be concluded from these tests that: orifice design has a controlling effect on shape. For a symmetrical part the split die or ring type orifice should be used, (other shapes could be formed with various size exhaust ports). The billet height to diameter ratio required to produce a shape could be reduced by feeding the stock from both sides.

An advantage of a tubular blank is the amount of work the material would undergo to make a disc could be reduced by flowing the material to the inside (I. D.) diameter at the same time as the outside (O. D.) diameter (Figure 12).

Figure 8. Typical flow pattern of laminated clay upset into a cavity.

Figure 9. Multi-ring aluminum die for use with clay flow studies.

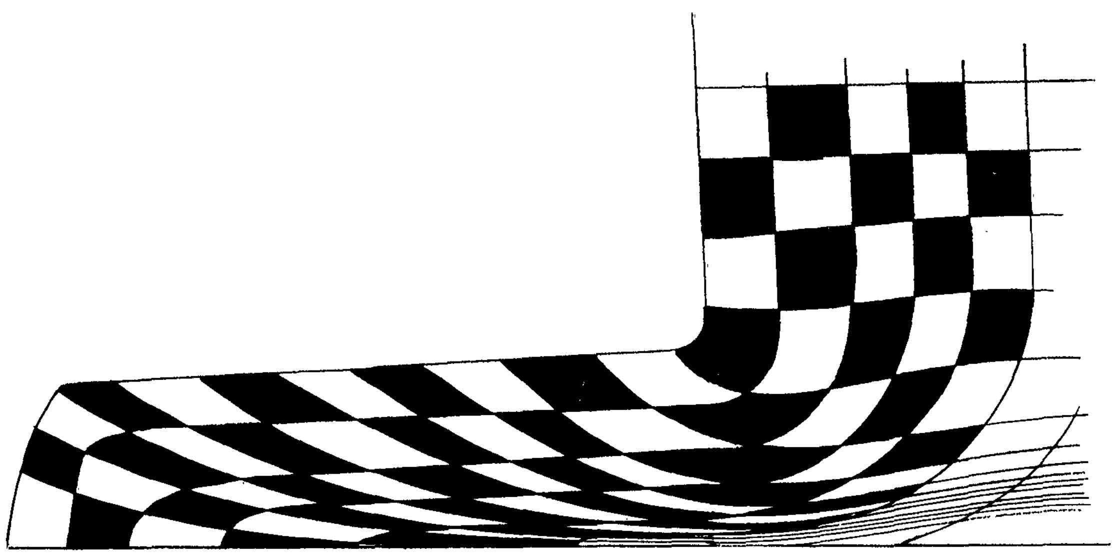


Figure 10. Superimposed flow pattern of the two clay laminates.

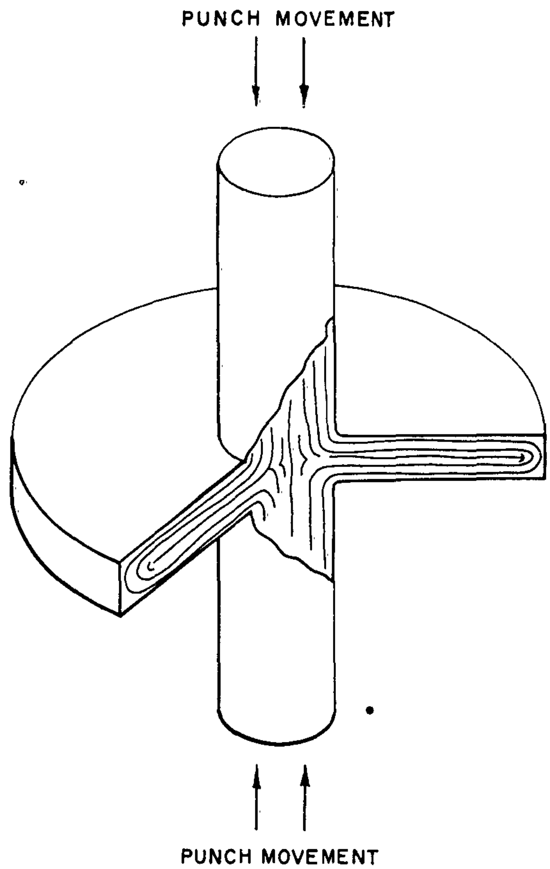


Figure 11. Possible method of reducing length/diameter ratio of billet for large volume parts by feeding stock from both sides of die.

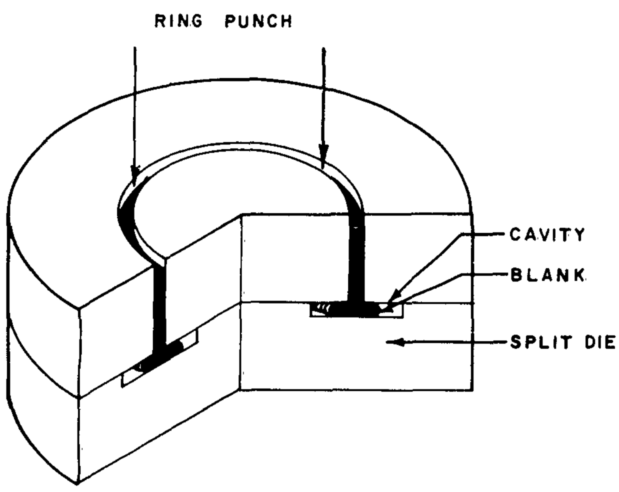


Figure 12. Possible method of reducing length/diameter ratio of billet for high upset ratios and reduce the amount of work on the material formed.

MATRIX TESTS

A suitable matrix material for the die system to be used for this contract needs to be viscious to keep the sealing problem under the high pressures to a minimum, but still be able to transmit pressure hydrostatically.

Six materials were tested by extruding them through various orifice sizes and length; lead, cerrobend, Wood's metal, Asarco Lo 117, Asarco Lo 281 and mold wax.

The subject material was introduced into 7/8" diameter chamber as a preform cylinder. A press driven punch caused extrusion of the material out radial holes or a split at the bottom of the chamber.

The cubic inches of material extruded was determined by timing the extrusion of a known quantity of material. This is plotted vs the unit pressure required in Figure 13.

There are no curves for Asarco Lo 281 or mold wax since materials could not be extruded within the pressure limitations of the setup.

The other materials, with the exception of Wood's metal, exhibit a linear relation between applied force and extrusion rate. Wood's metal extruded in steps. Apparently the liquified metal recrystalized during extrusion and required additional pressure build-up to liquify again.

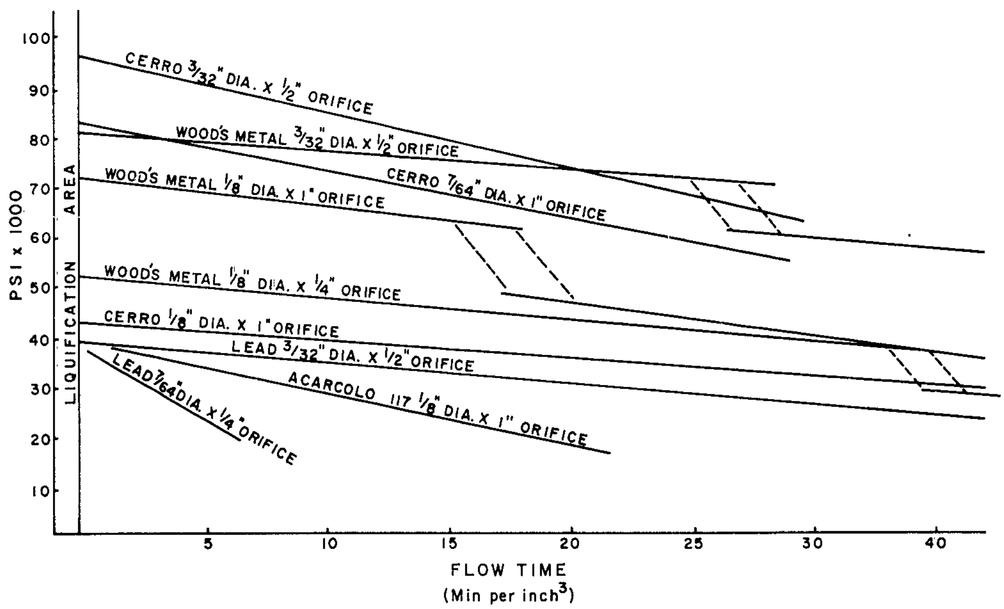


Figure 13. Plot of pressure required to extrude a given volume of matrix material through various orifice configurations.

LUBRICATION TESTS

Since the unit loading involved in upsetting materials at room temperature are high, tests were conducted to determine how the most promising matrix materials compared with various lubricants.

The tests involved the upsetting of cylindrically shaped specimens (.750" diameter x 1.00" high) of A.I.S.I. 4340 to exactly half their height.

The ends of the specimens were machined, polished and coated with the lubricant to be compared. Lubricants and matrix checked were: lead, mineral oil, glass, teflon, colloidal graphite, and cerrobend. Lubricating qualities were measured as a function of end restraint on the final diameter of the cylinder ends. Figure 14 shows two of the specimens tested, the barreled part had no lubricant, the other cerrobend.

Test No.	Lubricant	Average End Diameter
1a	None	.9026
b		.9051
2a	Lead	.9782
b		.9833
3a	Cerro	.9974
b		1.0020
c		1.0015
d		1.0010
4a	Mineral Oil	.9458
b		.9473
5a	Glass	.9458
b		.9473
6a	Teflon	.9949
b		.9910
7a	Colloidal Graphite	1.0010
b		.9906

Table I

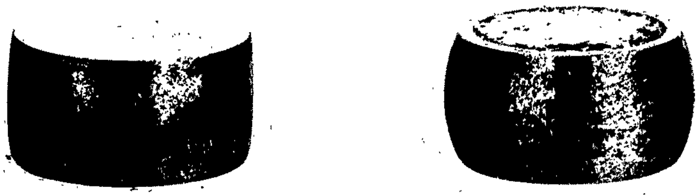


Figure 14. Billet on the left was upset with cerrobend as a lubricant, the billet on the right had no lubrication.

FORGING TESTS

The main purpose of the initia ᶠ˜rging trials was to evaluate the die system and forging technique. This wa. ̶ done by upsetting aluminum into the die cavity to the maximum ratio of 19:1 (based on billet and cavity area). Some steel was also tried to test the high pressure capability of the die, one test took the punch to failure or 540,000 psi 90% of design operational requirement of the tooling.

For the die tryout billets only the cavity pressure was changed for a given material, all parts were formed with rate as a constant.

The die insert used, 1-5/8" diameter provided a pocket .100" thick.

The aluminum billets were machined from 1100 bar stock annealed to 32 BHN (500 - kg load, 10-mim. ball). The steel billets were machined from vacuum melted A.I.S.I. 4340 after a 72-hour spheroidizing cycle.

Upset ratios were controlled by the length of billet stock pushed into the die, the maximum ratio being 19:1. Forming rate with the equipment can be varied from 5 inches per minute down to .02 inches per minute or less.

Based on previous tests and the information gathered for this report, cerrobend was used for the matrix material because of its lubrication qualities and its properties under high pressure.

In conducting the tests, the pressure in the cavity was set by varying the clamping pressure of the dies. For any given clamp pressure a definite cavity pressure had to be built up to cause separation of the dies and allow the matrix to be exhausted. This occurred when the cavity pressure times its ares just exceeded the clamping force. The cavity pressure is also monitored by a pressure probe

(Figure 15). A Budd Metalfilm gage mounted on a carbide pin and read with a Baldwin SR-4 strain indicator gives the cavity pressure at the maximum diameter. Under setup conditions a pressure transducer in the punch ram hydraulics provides the cavity pressure at the center or the total force necessary to upset the billet into the matrix-filled cavity plus overcome the friction of the complete system.

To establish a basis for determining the effect of back pressure on the aluminum's ability to be upset into such a die system, a number of billets were processed with no matrix. The maximum upset ratio achieved without fracture was 4:1 (Figure 16).

A number of aluminum billets were then upset with different levels of back pressure in the cavity (Figure 17). As a general observation, the cracks became less severe as the pressure was increased. At 20,000 psi to 30,000 psi, depending on the upset ratio, there is no evidence of cracks. It was also noted the discontinuities in the top surface of the formed part indicating a differential stress existed across the thickness during deformation. This along with the edge appearance shows the matrix material is not being exhausted from the top surface of the cavity.

It would be desirable to have the billet upset in such a manner that it would appear to extrude in a radial direction. This could occur by a incremental expansion of the part diameters. As the part is formed the outer diameters of the part are expanded due to the introduction of new stock at the center. As the diameter increases the part thickness tends to decrease, to prevent this edge thinning a hydrostatic pressure sufficient to upset the edge re-establishes the part thickness.

In order for this to happen, the billet must seal the cavity at the start of the deformation and maintain it throughout the operation.

Observation of parts just started to deform in the cavity, are mushroomed such that the cavity pressure act on the top surface as well as the diameter. To create a seal at the onset was first accomplished by machining and later by an upset operation. This was done by using the closing action of the dies to upset an extended length of billet prior to the actual pressure forming.

The same series of tests were run as before, the only difference being the preshaped seal (Figure 18). Again the cracking can be noted at the low back pressures and decreasing in magnitude as the pressure is increased until no cracks are apparent. The top surface on these parts do not show any discontinuities on the surface and the edge is square and normal to the part face.

Cavity P.S.I.	Upset Ratio	Matrix	Clamp Press Tons	Ram P.S.I.	Remarks
0	2.0	None	50	16,200	No Cracks
0	3.8	None	50	16,200	No Cracks
0	4.0	None	50	16,200	Surface Cracks
0	4.7	None	50	16,200	Split Open
0	6.0	None	50	16,200	Split Open
0	7.0	None	50	16,200	Split Open
Recording Problem	7.0	Lead	25	Recording Problem	Surface Cracks
	7.0	Lead	50		No Cracks
	11.0	Lead	50		Cracked
	12.0	Lead	25	80,900	No Cracks
	15.0	Lead	50	81,000	No Cracks
10,000	15.0	Cerro	25	26,700	Cracked
10,000	15.0	Cerro	25	26,800	Cracked – Sealed*
16,000	15.0	Cerro	30	32,400	Cracked
16,000	16.0	Cerro	25	32,200	Cracked – Sealed*
21,000	15.0	Cerro	45	38,000	No Cracks – Matrix Trapped
20,400	16.0	Cerro	40	36,400	No Cracks – Sealed*
25,500	19.0	Cerro	50	41,700	No Cracks, Fold
32,000	16.0	Cerro	50	48,600	No Cracks
32,000	15.0	Cerro	35	48,600	No Cracks – Sealed*
40,000	14.0	Cerro	50	56,700	No Cracks – Sealed*
100,000	13.0	Dux Seal	100	129,000	No Cracks – Non Uniform Flow
100,000	15.0	Dux Seal	100	129,000	No Cracks –
100,000	16.0	Dux Seal	100	129,000	No Cracks –

* Blank used was preformed as shown in Figure 18.

Table II.

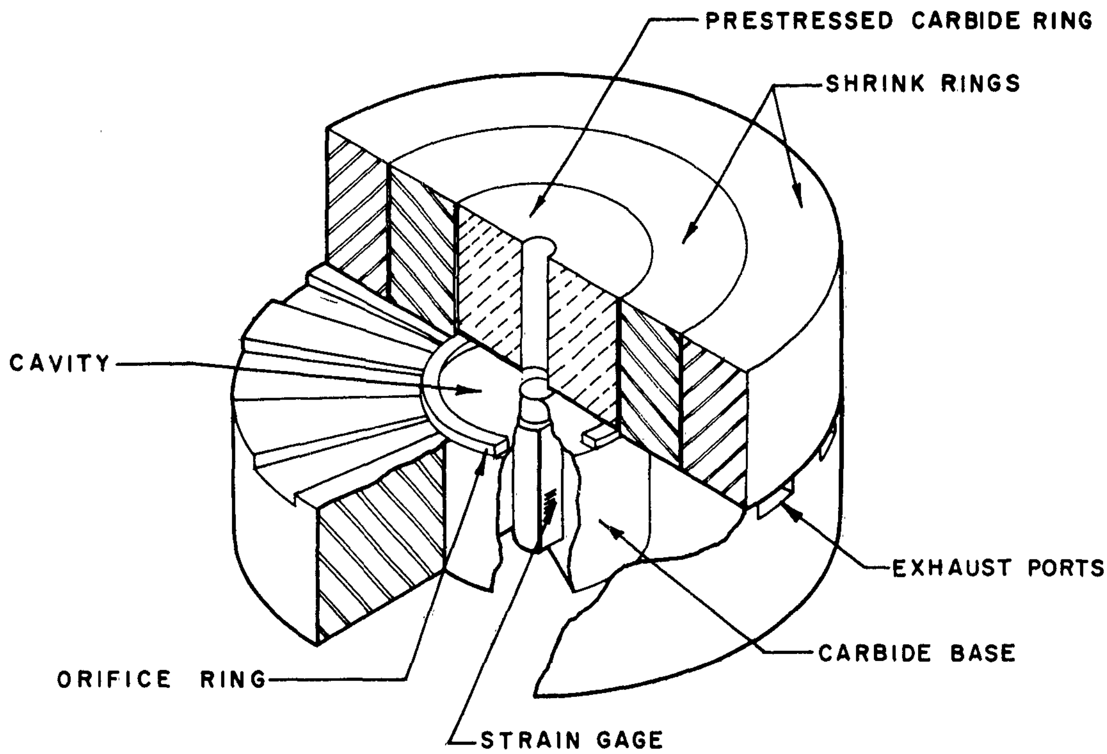


Figure 15. Die setup showing method of measuring cavity pressure with strain gaged carbide probe.

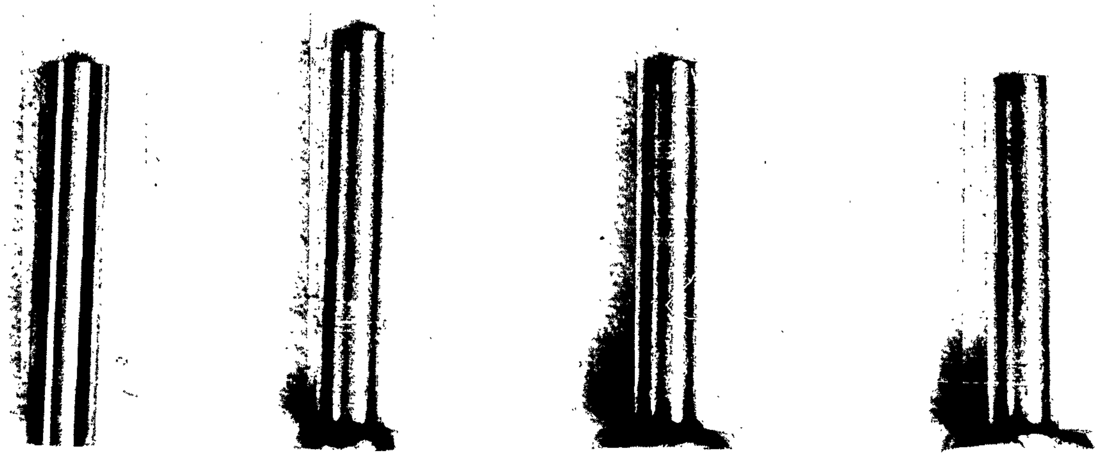
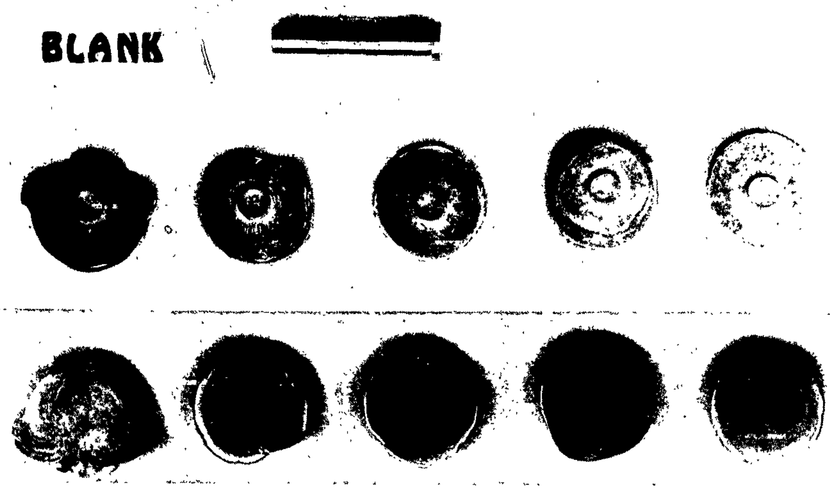


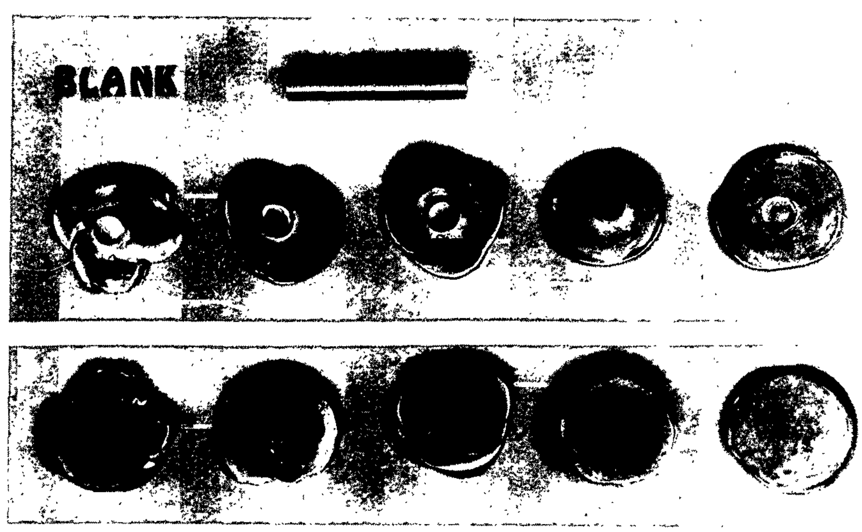
Figure 16. 1100F aluminum upset into the die cavity with no back pressure. The maximum upset ratio without fracture attainable was 4:1.



0 10 15 20 30

Cavity Pressure (1000's p.s.i.)

Figure 17. 1100F aluminum billets upset into a die cavity of cerrobend starting with a straight billet.

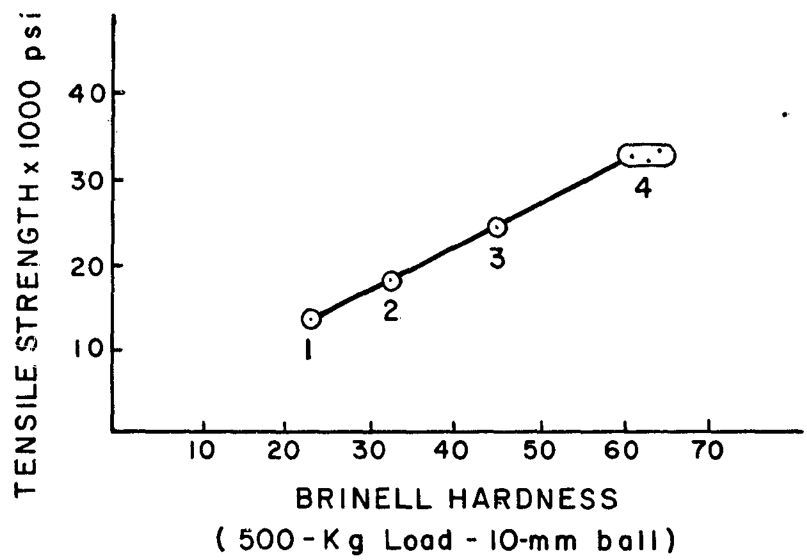


0 10 15 20 30

Cavity Pressure (1000's p.s.i.)

Figure 18. 1100F aluminum billets upset into a die cavity of cerrobend starting with a preshaped billet to seal the cavity.

To develop as much information out of the test as possible, an estimate of tensile strength of the material was made based on hardness (Figure 19). From this preliminary data it would appear the hydrostatic pressure has to be in excess of the tensile strength of the material being worked to allow increased deformation.



(1) ANNEALED

(2) HALF HARD (H-14)

(3) FULL HARD (H-18)

(4) ANNEALED + H.C. FORGING

Figure 19.

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Lear Seigler
Astro Structures Division
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